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Design and development in optics of concentrator photovoltaic system

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ABSTRACT

Due to the dramatic advances in commercial multi-junction solar cells with 40% conversion efficiency, solar concentrator capable of delivering flux levels of hundreds to thousands of suns at high collective efficiency is the key factor for the success of novel Concentrator Photovoltaic (CPV) system. This paper would review and survey the progress in the last 30 years including the optical design and development in the optics of solar concentrators for the CPV system. The detailed architectural design and optical principle of solar concentrators are presented to show various innovative and creative ideas of harnessing solar energy.

Contents

1. Introduction

In the past few years, we have witnessed a paradigm shift in photovoltaic power generation [1]. It stems from the confluence of dramatic advances in commercial high-efficiency multi-junction solar cells capable of 40% conversion efficiency, and optical design in solar concentrators capable of delivering flux levels of hundreds to thousands of suns at high collective efficiency. In the high concentration systems, even with cells that are two orders of magnitude more expensive on an area basis than conventional photovoltaic (PV), the cost contributed by the cell becomes attractively low. The burden then shift to the optical design to provide a cost-effective and practical system. The focus is on the new classes of high-flux, ultra-compact, practical optics, traced from initial concepts through commercial realization. Concentrator Photovoltaic (CPV) system can be built with high photonic-to-electric efficiencies [2]. The most advanced solar cell actually performs better in focused sunlight than with ordinary sunlight. State-of-the-art triple-junction cells have been developed with 40–41% efficiency at 100–900 times concentration, the world record presently being 41.1% at 454 times concentration [3]. Law et al. from Boeing-Spectrolab Inc (2010) have discussed on future terrestrial concentrator cells that will likely feature four or more junctions. The better division of the solar spectrum and the lower current densities in these new multi-junction cells reduce the resistive power loss and provide a significant advantage in

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achieving higher efficiencies of 45–50% [4]. Interest in CPV grew substantially after promoting in practice that higher-efficiency multi-cascade solar cells demonstrated a perspective to achieve photovoltaic conversion efficiencies as high as 40–50% [5].

Boes summarizes the progress that has been made in 1990 in the area of photovoltaic concentrator technology development [6]. A brief description of the status of two photovoltaic concentrator power systems is given: the 300 kW ENTECH-3M-Austin system and the single-pedestal Alpha Solarco system. The paper emphasizes those module development activities that have resulted in significantly higher conversion efficiencies or new module design concepts. Whitfield et al. compared some 90 possible small PV concentrator designs that might be suitable for use at remote sites [7]. They had apertures of about 2 m^2, used BP solar LBG cells, and employed small aperture module to reduce heat sinking and construction costs. The designs included fixed V-troughs and Compound Parabolic Concentrators (CPCs), single axis tracked cylindrical lens and mirror systems, and two axis tracked spherical-symmetry system. Performance and volume production costs were estimated. Several designs of small concentrator systems can be significantly cheaper than conventional planar arrays, reducing cost/watt and cost/kWh by a factor of 2 or 3. To achieve such reduced costs, the concentrators should be designed to use minimum amount of material, and be manufactured in such a way, and in sufficient quantity, as to keep down the manufacturing cost. In addition, CPV systems have a number of unique attributes that could shortcut the development process of producing hydrogen [8]. The development of efficient, renewable methods of producing hydrogen is essential for the success of the hydrogen economy. The development of a hydrogen economy can have many benefits for the environment. It can play a role in reducing global warming and air quality problems in and around major cities.

Durability and reliability of CPV system are the major concerns due to the effects of ageing and soiling especially on the optical material that cause significant reduction in electrical output. Miller and Kurtz have carried out literature review on the durability of Fresnel lenses specific to the concentrating photovoltaic application [9]. The review includes the topic of optical durability, discoloration, soiling and accumulation of particulate matter etc. Vivar et al. has studied the effect of soiling in CPV systems [10]. The effect of soiling in flat PV modules has been already studied causing a reduction of the electrical output of 4% on average. For CPV, as far as soiling produces light scattering at the optical collector surface, the scattered rays should be definitely lost because they cannot be focused onto the receiver again. Some experiments have been conducted by Vivar et al. at the IES-UPM and CSES-ANU sites, consisting in linear reflective concentration systems, a point focus refractive concentrator and a flat module. In general, CPV systems are more sensitive to soiling than flat panels, accumulating losses in short-circuit current of about 14% on average. Appropriate design of optical system to minimize dust particle trapping and cleaning implemented at an economically optimized frequency are important to improve the electrical production.

2. Types of solar concentrator and optical design

Solar concentrator system employs either lenses or reflectors or a combination of both types associated with tracking system to concentrate a large area of sunlight onto a small beam. Some concentrator system also employs secondary concentrator or even tertiary concentrator to enhance the solar concentration ratio as well as to homogenize the distribution of solar flux on the receiver. CPV panel is more sensitive than a heat receiver to the distribution of focused sunlight and therefore it requires a proper optical design of concentrator that is capable of spreading the focused sunlight evenly over the receiver surface. Although there are wide ranges of concentrating technologies exist in worldwide, all these optical technologies can be fundamentally categorized into five major groups based on their primary focusing method: linear focusing lens, two-dimensional focusing lens, linear focusing reflector, two dimensional focusing reflector and central receiver system. The architectural designs and optical principles for various solar concentrators specially tailored for the CPV systems are depicted and presented in the following section.

2.1. Linear focusing lens

Leutz et al. designed an optimum convex shaped non-imaging Fresnel lens according to the edge ray principle [11]. If a secondary concentrator and a diffuser are provided, non-tracking operation is possible and the irradiance should be well distributed over the photovoltaic panel. The schematic diagram is given in Fig. 1 where the flux concentration in such a system is around 15–20 times. The proposed truncated non-imaging Fresnel lens offers the advantage of requiring only passive tracking and seasonal tilt. Chemisana et al. proposed a photovoltaic-thermal module for Fresnel linear concentrator by combining a domed linear Fresnel lens as primary concentrator (5 ×), a compound parabolic reflector as secondary concentrator (2 ×) and a photovoltaic-thermal module [12].

O'Neill patented a high efficiency, extremely light-weight, and robust stretched Fresnel lens solar concentrator coupled to photovoltaic concentrator array for generating power in space [13]. The stretched Fresnel lens solar concentrator consists of a flexible Fresnel lens attached to end supports to maintain its proper position and shape as shown in Fig. 2.

2.2. Two-dimensional focusing lens

Jebens and Skillman patented Fresnel lens concentrator that is formed by a specially designed Fresnel lens and a solar cell located on the axis of the lens at its focal plane as depicted in Fig. 3 [14]. The lens is designed so that its central facets project the light from the sun towards the outer periphery of the cell and facets progressively toward the periphery of the lens project light progressively toward the center of the cell to obtain a uniform distribution of light on the cell. Adjacent groups of facets of the lens project the light alternatively in front and beyond the cell to maintain a constant light intensity for a certain depth of focus of the lens.

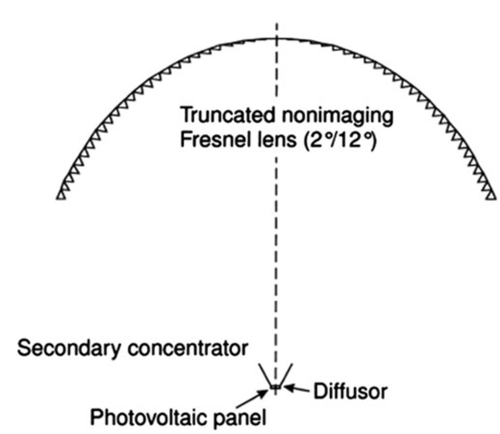

Fig. 1. Schematic of truncated non-imaging Fresnel lens with secondary concentrator for application in photovoltaic systems.

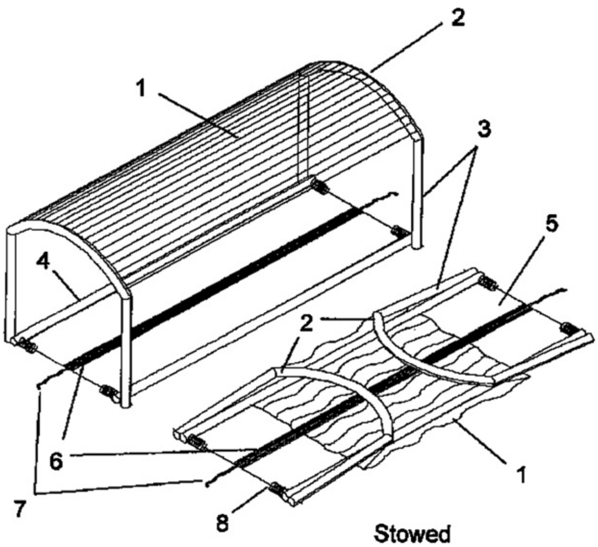

Fig. 2. A perspective view of a deployable embodiment of stretched Fresnel lens solar concentrator for space power.

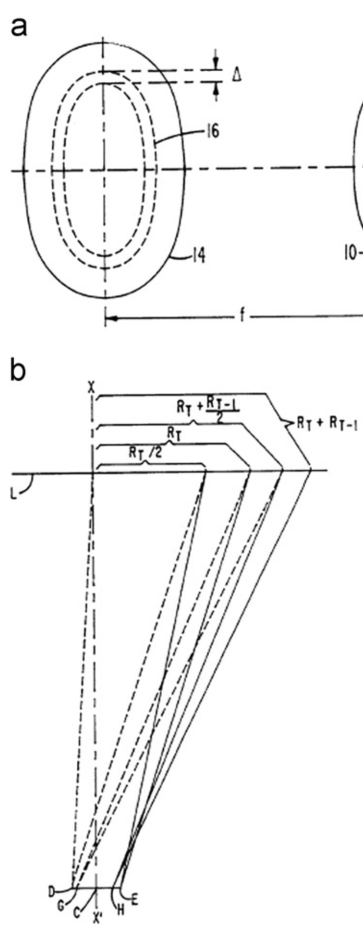

Fig. 3. (a) Schematic view of Fresnel lens with an intermediate facet and a circular target with an intermediate ring, (b) Diagrammatic view of the direction of some light beams going from the lens to the target.

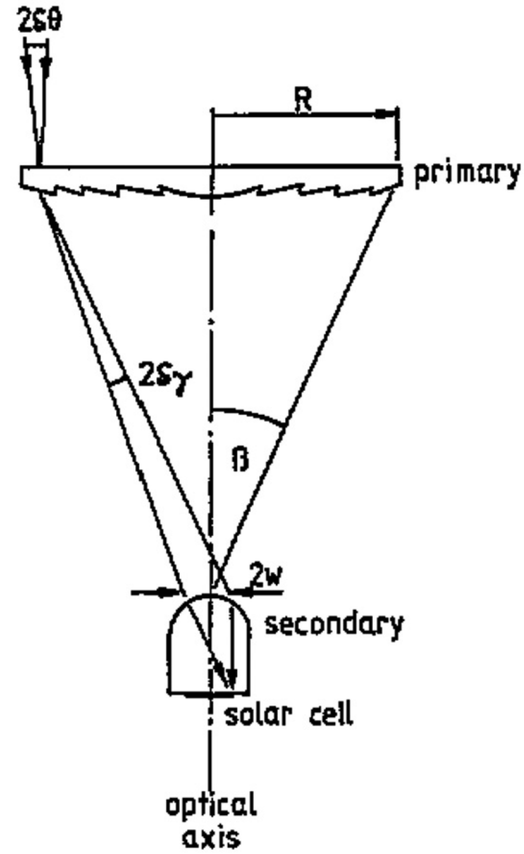

Fig. 4. Sketch showing a cross section through a two-stage, axially-symmetric concentrator with Fresnel lens as primary and single-surface spherical lens as secondary.

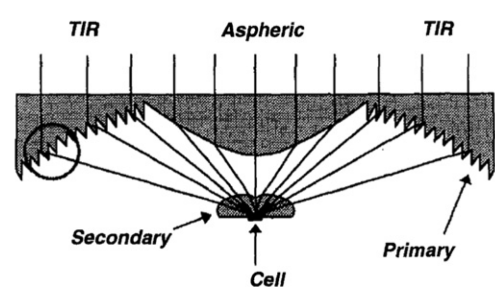

Fig. 5. TIR-R concentrator with detail of TIR lens.

Davies studied the design of single-surface spherical lens as secondary concentrator in the two-stage concentrator with Fresnel lens as primary stage [15]. Fig. 4 shows a cross section view of a two-stage, axially-symmetric concentrator with Fresnel lens as primary whose first surface is flat and single-surface spherical lens as secondary in the form of a domed pillar glued to the cell. In this design, Fresnel lens with maximum concentration of about 100 times at *f*/1.37 has been improved in the two-stage concentrator system to maximum concentration of 530 times at optimal *f*-number of *f*/2.84.

Terao et al. proposed a non-imaging optics design for a flat-plate CPV system [16]. In Fig. 5, the design consists of a conventional primary/secondary lens combination, but uses aspheric and total internal reflection lens components in the primary to reduce the focal length and hence the thickness of the whole module. Ray-tracing simulations indicates that an acceptance angle in excess of $\pm 2.6^\circ$ can be achieved, which makes the design suitable for light-weight, low-cost tracking systems.

Chen patented a stationary solar photovoltaic array module design, which constitutes three or four steps of optical concentrations of photovoltaic power generation system [17,18]. The concentrator can have either one layer (2004) or two layers (2003) of Fresnel lens concentrating sunrays. A compound

parabolic concentrator (CPC) is mounted under a first or second Fresnel lenses to further concentrate the intensity of sunlight with twenty times more. Then, the concentrated sunlight is homogenized as it passes through a third or fourth optical concentrator glass lens with anti-reflection coating on the top surface just before incident on the multi-junction solar cell. Fig. 6 shows the combination of multi-stage Fresnel lenses and optical reflectors which can concentrate solar intensity 300 to 1000 times within a six-inch distance.

Andreev et al. proposed a modified structure of the high concentration all glass PV modules for a solar-powered Thermo-Photovoltaic (TPV) system with III–V solar cells [19]. Main structural features of the concentrator modules under development are the following: small aperture area and short focal length Fresnel lenses as the primary concentrators; lens panels with a composite (glass–silicone) structure; "all-glass" module design, which implies that all the main parts of a module cabinet are made of conventional silicate glass. In the all glass module design, the secondary lenses arranged in an intermediate composite (glass–silicone) panel is inserted between a panel of the primary composite Fresnel lens concentrators and a panel of the solar cells as shown in Fig. 7.

Ryu et al. proposed a new configuration of solar concentration optics utilizing modularly faceted Fresnel lenses to achieve a uniform intensity on the receiver plane with moderate concentration ratio [20]. Fig. 8 reveals that the uniform illumination is obtained by the superposition of flux distribution resulted from modularly faceted Fresnel lenses. The flux distribution at the cell plane are estimated to be uniform within $\sim$20% with transmission efficiency larger than 65% for 3×3, 5×5 and 7×7 arrays of Fresnel lenses. With $f/1.2$, the intensity levels of various concentration ratios are 7 suns for the 3×3 array, 19 suns for the 5×5 array, 31 suns for the 7×7 array, 47 suns for the 9×9 array, and 60 suns for the 11×11 array, respectively.

Winston and Ritschel patented an optical device that consists of a primary Fresnel lens and secondary non-imaging optics to provide high solar flux onto a multi-junction solar cell for producing efficient

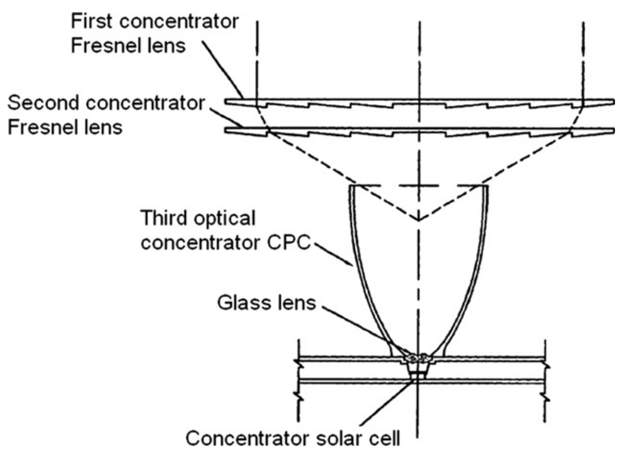

Fig. 6. Stationary photovoltaic array module design with sequence from top to bottom: First concentrator Fresnel lens for focusing sunrays five to ten times, second concentrator Fresnel lens, third optical concentrator CPC, fourth optical concentrator: a specially shaped glass lens, and concentrator solar cell with a 45% conversion efficiency.

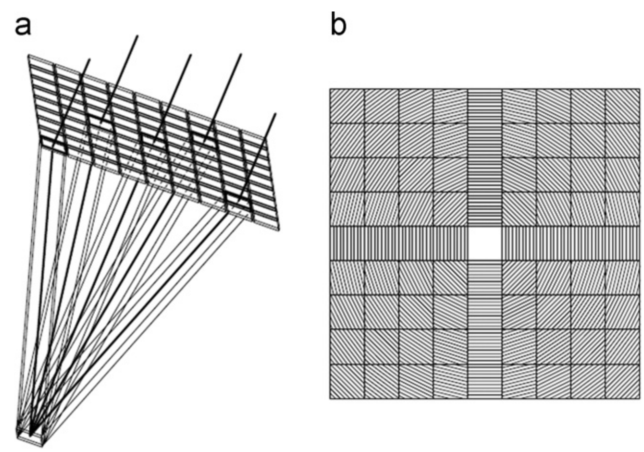

Fig. 8. Optical design concept of modular Fresnel lenses for solar flux concentration: (a) 3-D of concentration optics (b) facet directions of modularly faceted Fresnel lenses.

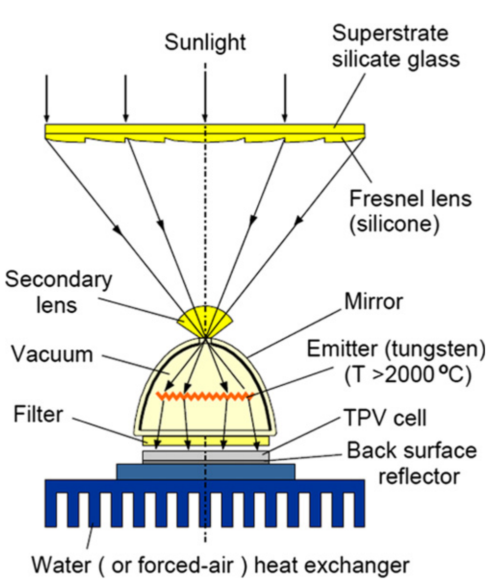

Fig. 7. Optical design concept of a modified structure of the high concentration all glass PV modules for solar-powered TPV system with high temperature ($T>2000$ °C) vacuum bulb emitter.

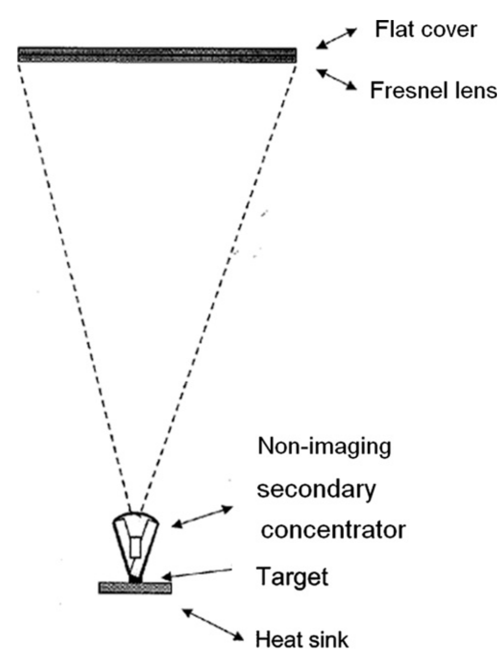

Fig. 9. Concentrating photovoltaic system using Fresnel lens and non-imaging secondary optics.

electrical output as illustrated in Fig. 9 [21]. The primary Fresnel lens with an *f*-number of greater than 1 (e.g., between 1 and 4 or greater) is configured to focus light from a distant source onto the entry aperture of the secondary concentrator. The solar cell is located at the exit aperture of the secondary concentrator. The optical device has an optical acceptance angle of about $\pm 5^{\circ}$ or greater with an optical efficiency of about 80–85%. It can be configured with a 125 mm × 125 mm entry aperture and a depth of about 230 mm to provide a geometric concentration of about 500× for 5.5 mm × 5.5 mm multi-junction cell and 150× for 10 mm × 10 mm Si cell.

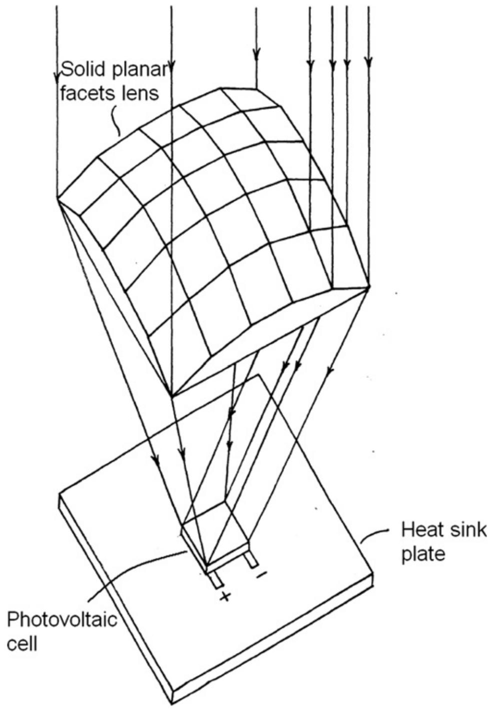

Fig. 10. Perspective view showing a solid lens with 25 planar facets on the top side facing the sun and a planar surface on the bottom side facing the photovoltaic cell mounted on a heat sink plate.

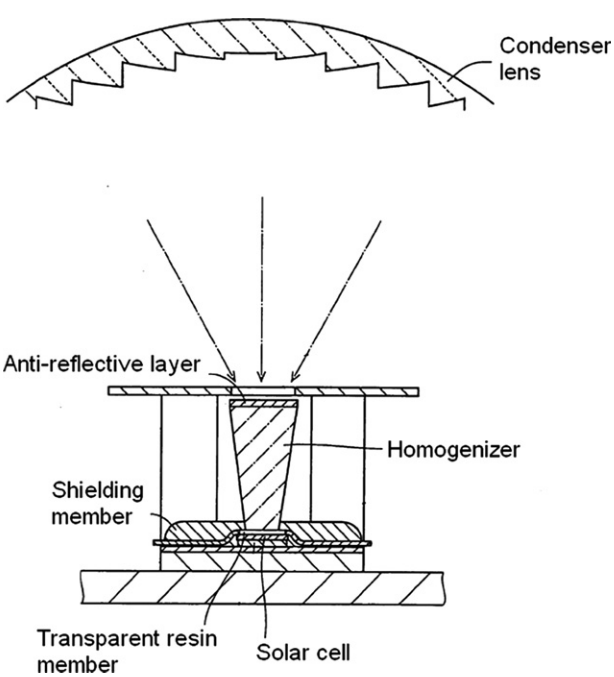

Fig. 11. A generation module of a concentrator solar photovoltaic apparatus which comprises of a plurality of generation modules disposed within in an enlarged cross sectional view.

Schwartzman designed a solar energy concentrator lens formed by a prism array [22]. Fig. 10 shows how each prism of 25 planar facets is designed to deflect the incident solar rays and fully illuminate a rectangular photovoltaic cell with uniform intensity. The combination of multiple prisms uniformly illuminating a common target area yields concentrated uniform illumination across the target area.

Araki et al. patented a concentrator solar photovoltaic apparatus including a primary optics for concentrating sunlight, a columnar optical member, and a transparent resin member and the solar cell (refer to Fig. 11) [23]. A columnar optical member or homogenizer acting as secondary optics is used for guiding the sunlight, which is concentrated by the primary optics to the solar cell.

Ota and Nishioka proposed a 3-D simulation for concentrator photovoltaic module using triple-junction solar cell by connecting ray-trace simulation for an optics model and 3-D equivalent circuit simulation for a triple junction solar cell. It has been used to study a typical flat Fresnel lens (110 mm × 110 mm in entry aperture area and focal length 150 mm) and homogenizer (9 mm × 9 mm in entry aperture area, 4.5 mm × 4.5 mm in exit aperture area, and 35 mm in height) was set in the vicinity of the focal length of the Fresnel lens to have the effective geometrical concentration ratio of 597 times [24].

2.3. Linear focusing reflector

Singh and Liburdy presented a reflective concentrator capable of concentrating a collimated beam of light onto a flat receiver to

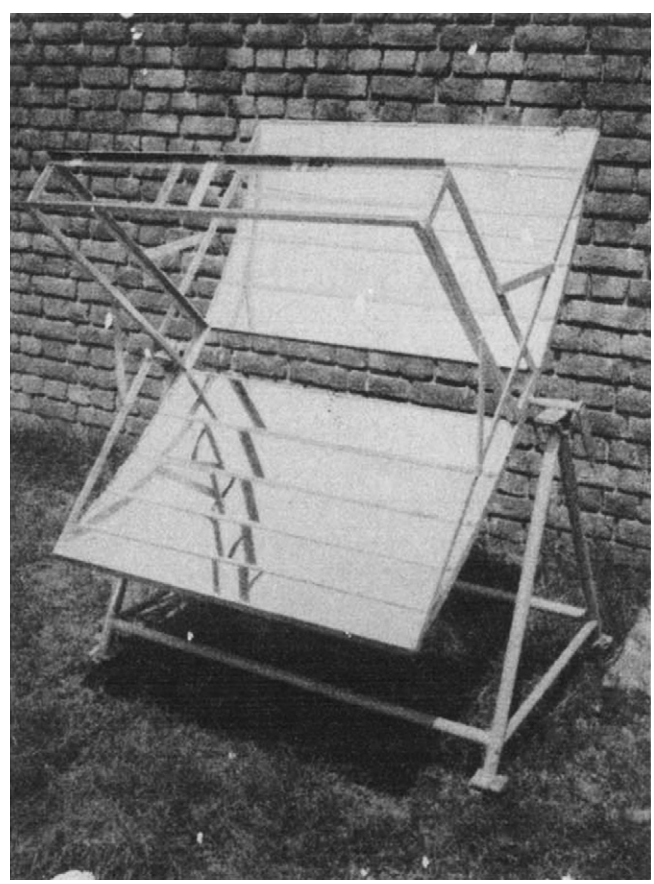

Fig. 12. Picture of the experimental solar concentrator consists of a series of flat panels of different sizes.

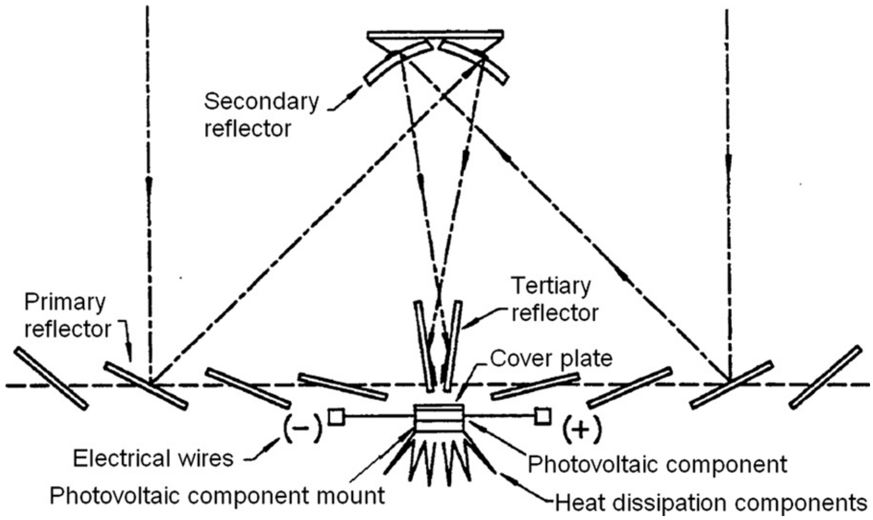

Fig. 13. A cross sectional schematic of multiple-reflector-concentrator module where the secondary reflector being placed at the focal line of primary reflector.

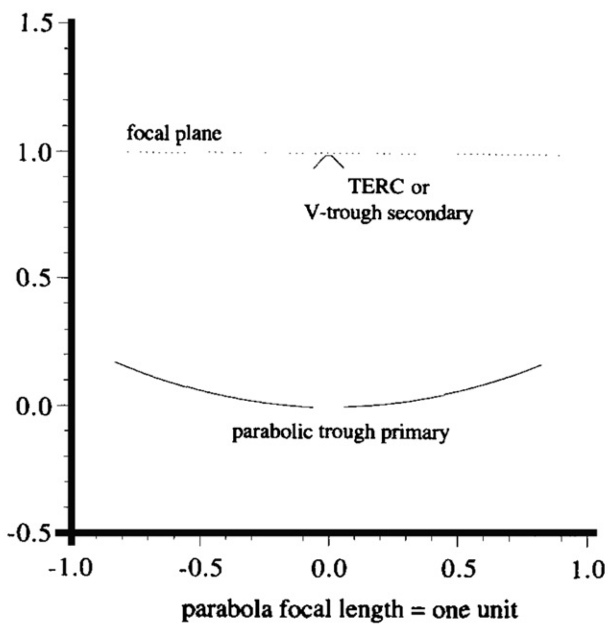

Fig. 14. Scale drawing of parabolic trough primary, TERC (or V-trough) secondary, and photovoltaic absorber. Parabola focal plane is also shown (above absorber).

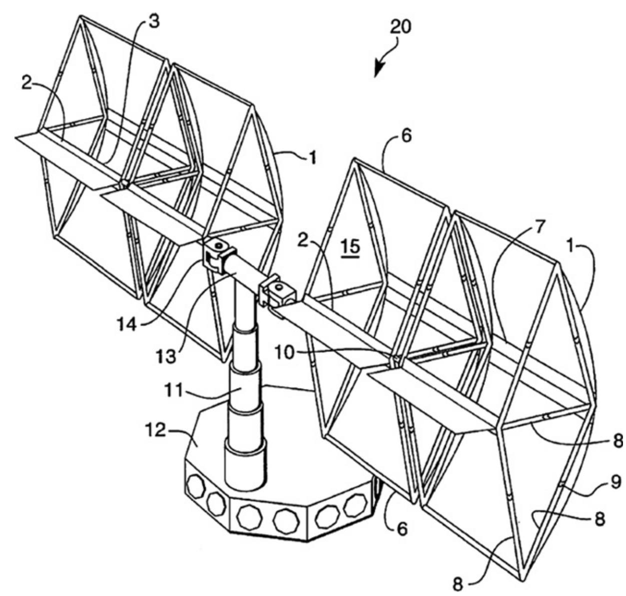

Fig. 15. Photovoltaic concentrator (20) with foldable struts (8) extended forming triangular frame section (15): End arms (6) are connected at the top and bottom of the triangular frame section (15) and are used to attach a reflective concentrator (1) to the structure. The reflective concentrator is an inflatable concentrator made of silvered Kapton film.

obtain a uniform flux distribution with the maximum theoretical concentration ratio of 22.79[25]. The main advantage of this design is that the reflector consists of a series of flat panels of different sizes enabling the use of commercially available plane mirror as shown in Fig. 12. Measurement of the flux on its receiver indicates a quite uniform flux distribution in about 80% of the receiver area.

Lamb and Lawrence patented multiple-reflector concentrator to concentrate sunlight onto a panel of photovoltaic cell in a solar electric power system as shown in Fig. 13 [26]. The power system, consisting of multiple reflectors, mounted PV cells and a heat dissipation component, is mounted on a tracker that keeps the system directed to the sun. The system can operate on either a single or dual axis tracker with active or passive tracking.

Gordon presented the optical design for a high-efficiency linear photovoltaic solar concentrator assembled from readily-available inexpensive components as shown in Fig. 14 [27]. Accounting for all geometric and material-related optical losses, he found that it should easily produce flux levels of 50–100 suns with homogeneous irradiance of the absorber. The specification of the system components are as follow: parabolic focal length is 1.49 m and the parabola entrance aperture width is 2.47 m; the solar cell width is 0.033 m; the secondary V-trough has a depth of 0.072 m and an entrance width of 0.176 m.

For the project EUCLIDES (EUropean Concentration Light Intensity Development of Energy Sources), Sala et al. developed a one axis horizontal tracking, North/South oriented parabolic trough reflector for CPV system [28]. The geometric concentration ratio is 32 and the overall efficiencies of 14 series connected receiving modules are 15% at the temperature of 25 °C. Such modules consist of 12 BP solar SATURN concentrator cells fully encapsulated.

Clemens disclosed a light weight photovoltaic concentrator having a foldable, easily deployed structure for concentrating sunrays on solar cells for generating electricity [29]. The concentrator can be inflated to a shape of parabolic trough for focusing sunlight onto the solar cell at the ratio of 20 suns. The inflatable

concentrator is inflated by gas stored in the central arm which supports one end of the concentrator. The concentrator is inflated until the epicenters of the front and rear surfaces reach a specified distance and the concentrator is thereafter maintained at this position as shown in Fig. 15.

Frazier patented a double reflecting solar concentrator utilizing a primary reflective surface (parabolic mirror) which reflects incident light toward a secondary surface (directrix plane) [30]. The incident light reflects off the secondary surface away from the primary surface's natural focus point toward a secondary focal point positioned on or substantially near the surface of the primary reflective surface. The invention provides an exemplary double reflecting style of parabolic trough structure that is substantially more rigid than a simple parabolic surface where the photovoltaic cell can be placed along focal line as shown in Fig. 16.

Hein et al. achieved a high geometrical concentration ratio of 300 suns using a parabolic trough mirror and a three-dimensional second stage consisting of compound parabolic concentrators (CPC) [31]. In the design, the geometrical concentration of the first stage concentrator and the CPC are 39.7 and 7.7 times, respectively leading to the concentration ratio of more than 300 times. Fig. 17 shows the prototype of this concentrator system built at Fraunhofer Institute for Solar Energy (ISE).

Coventry published the performance of a prototype parabolic trough photovoltaic/thermal collector with a geometric concentration of 37 suns constructed at the Australian National University [32]. Measured results under typical operating conditions show thermal efficiency of around 51% and electrical efficiency around of 11% to result a combined efficiency of 69%. The measured illumination flux profile along the length shows significant variation with the peak flux intensities shown to be around 100 suns, despite the mirror shape error less than 1 mm for most of the mirror area. The impacts of the illumination non-uniformities due to shape error, receiver support post shading and gaps between the mirrors are shown to have a significant effect on the overall electrical performance.

Straka patented a non-imaging reflective trough that receives spectral energy and linearly reflects that energy onto a smaller area on one side of the device with geometric concentration of seven suns (see Fig. 18) [33]. The linearly reflecting trough concentrator has the geometry of a single slope-relief interval in a Fresnel lens, and in preferred embodiment comprises an array of plane facet reflectors connected continuously to form the base of the trough, a non-imaging focal point where a photovoltaic receiver is located, and a relief surface to connect the mirrors array to the receiver location. The concentrator comprises of array of plane mirrors oriented according to the negative profile of two interleaved linear Fresnel lens, where the slope of one is the relief of the other.

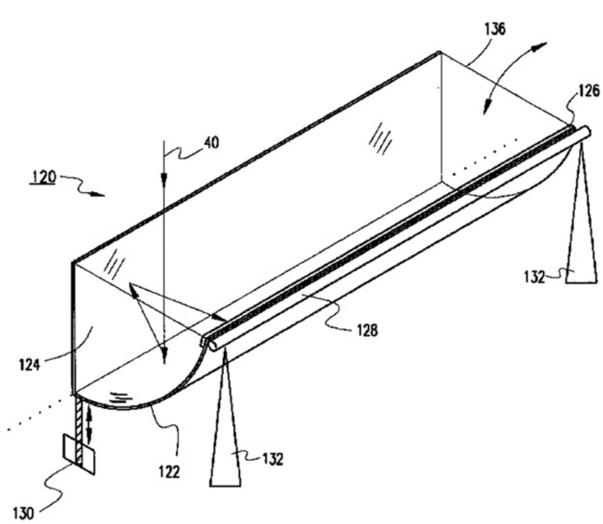

Fig. 16. A three-dimensional view of double reflecting solar concentrator (1 2 0) mounted on a support structure (1 3 2) and connected to hydraulic driving system (1 3 0): Incident light (40) reflects off the primary reflective surface (1 2 2) toward the secondary reflective surface (1 2 4) and then toward a solar collector or photovoltaic (1 2 6) located at the focal line.

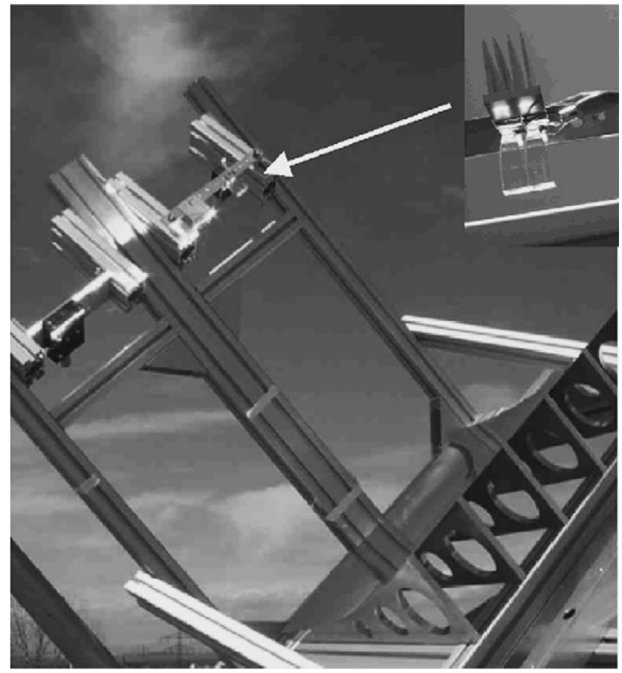

Fig. 17. Picture of a prototype of the concentrator module on a tracker. Two GaAs cells with CPCs have been mounted on heat sinks and installed in the focal line.

2.4. Two-dimensional focusing reflector

Jorgensen and Wendelin designed a multi-step-molded-dish concentrator capable of producing a uniform flux profile on a flat target plane [34]. Concentration levels of 100–200 suns, which are uniform over an area of several square inches, can be directly achieved for collection apertures of a reasonable size of approximately 1.5 m in diameter. For the arrangement as shown in Fig. 19, five concentric annular regions were arranged so that each annulus represents one fifth of the total aperture area. Each step section was offset along the optical axis and specified to be a spherical element whose curvature $1/2f$.

Ries et al. proposed and analyzed sample designs for a high flux photovoltaic concentrator comprised of a large-aperture paraboloidal-dish primary concentrator, and a second-stage kaleidoscope flux homogenizer [35]. Referring to Fig. 20, the design satisfied highly uniform irradiance on the solar cell absorber, high collective efficiency and not exceeding the prescribed target flux of 500 suns. The solution is to move the absorber out of the nominal focal plane, away from the dish, to a plane where the average concentration is 500 suns.

Feuermann and Gordon proposed a high concentration photovoltaic design based on miniature paraboloidal dish and kaleidoscope to achieve 1000 suns [36]. The collection unit is a miniature parabolic dish with a diameter of the order of 10 cm that concentrates sunlight into a short glass rod called kaleidoscope. The flux distribution of the transported light is homogenized in a miniature glass kaleidoscope that is optically coupled to a small,

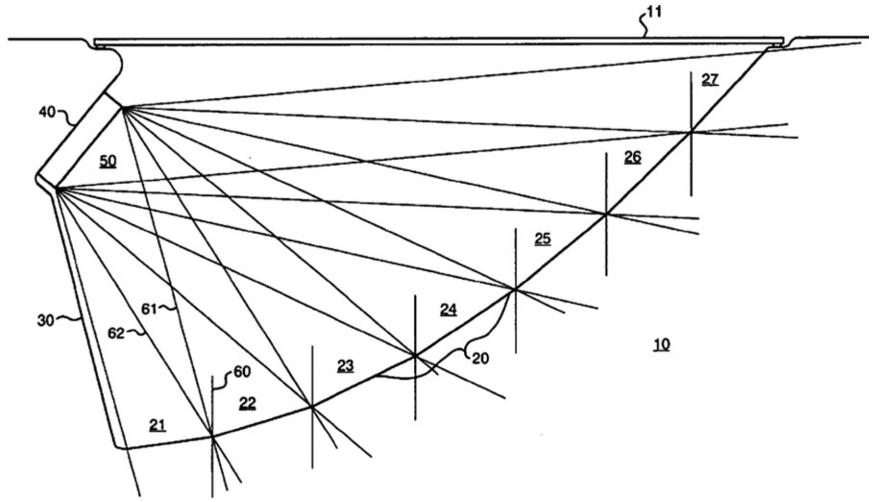

Fig. 18. Spectral energy (60) enters the aperture of the concentrator reflector (10) at an incident angle 90° to the horizontal plane. For seven plane facet mirrors (21–27) that are connected to form non-imaging reflective array, spectral energy is redirected onto solar receiver (50) for obtaining geometry concentration ratio of seven suns.

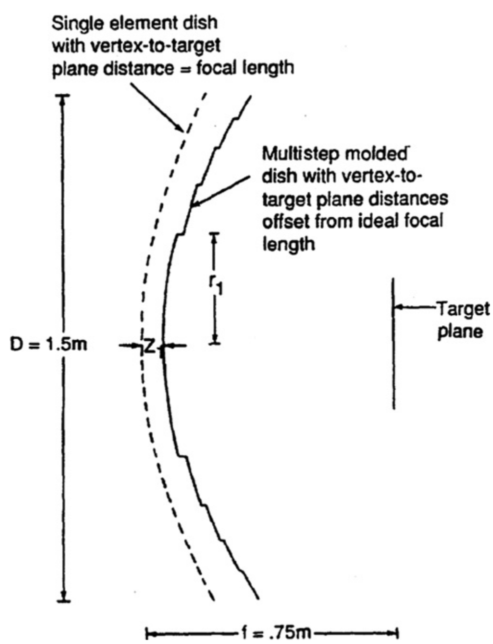

Fig. 19. Cross sectional geometry of 5-element molded dish.

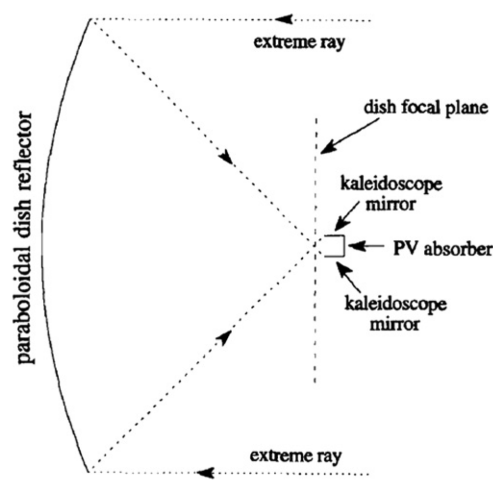

Fig. 20. Side view of the paraboloidal dish, its focal plane and the recessed kaleidoscope. The extreme rays from the dish cut the smallest waist in the focal plane, which defines its average concentration (e.g., 10,000). The kaleidoscope is recessed to a plane where the area delimited by the extreme rays corresponds to the prescribed concentration ratio (e.g., 500).

high-efficiency solar cell as illustrated in Fig. 21. The cell resides behind the dish and can be cooled adequately with a passive heat sink.

Kreske developed an optical solution for the redistribution of the light reflected from a 400 m^2 paraboloidal solar concentrating dish as uniform as possible over an approximately 1 m^2 plane as shown in Fig. 22 [37]. It is proposed that the solar cell will be mounted at the output of a rectangular receiver box with reflective sidewalls (i.e., a kaleidoscope or solar flux homogenizer) which will redistribute the light. From ray analysis, it is theoretically possible to achieve flux uniformity within the limits necessary for photovoltaic applications with a concentration ratio in the range of 500 suns.

Vasylyev et al. patented a non-imaging energy flux transformation system that includes a concentrator incorporating a set of nested, ring-like, concave reflective elements and a receiver as shown in Fig. 23 [38]. The system efficiently concentrates sunlight by means of focusing the energy striking the entrance aperture of concentrator to the receiver located on the side of concentrator's exit aperture. The mirror surface of the reflective elements having appropriate individual non-imaging profiles represented by curved or straight lines are positioned so that the energy portions reflected from individual surfaces are directed, focused and superimposed on one another to cooperatively form a common focal region on the receiver. The receiver can be an energy absorbing device (e.g., photovoltaic array), a secondary energy concentrating transformer or a flux homogenizer. Vasylyev then published the prototype of non-imaging reflective lens concentrators which provide solar concentration ratio of 1000 suns and flux uniformity on the rear of concentrator [39].

Terao and Krippendorf patented a compact micro-concentrator for photovoltaic cells that comprises of partial parabolic reflectors arranged in rows and columns with each reflector directing radiation to a photovoltaic cell [40]. In a compact photovoltaic cell arrangement, each cell is shielded from direct radiation by the adjacent reflector as depicted in Fig. 24. A secondary optical element, either reflective or refractive, can be provided with each cell receiver to further concentrate the reflected radiation to a photovoltaic cell at a more accessible location in the array.

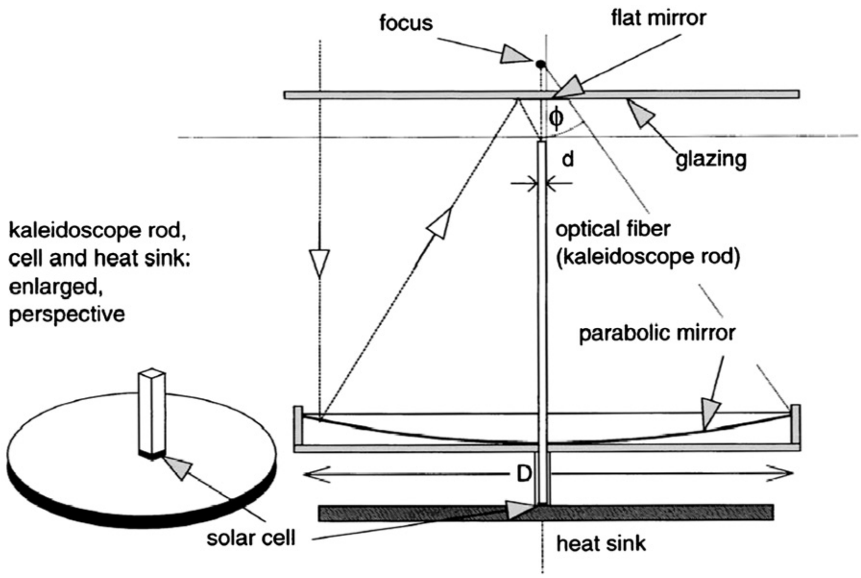

Fig. 21. Schematic illustration of a solar mini-dish photovoltaic concentrator: The parabolic mini-dish sits in an opaque encasement, except for the protective glazing. A small mirror deposited on the glazing redirects rays reflected from the mini-dish to the fibre's proximate tip, which is sited at a prescribed recession below the focal plane. A square cross section kaleidoscope optically couples the distal end of the fiber and the solar cell.

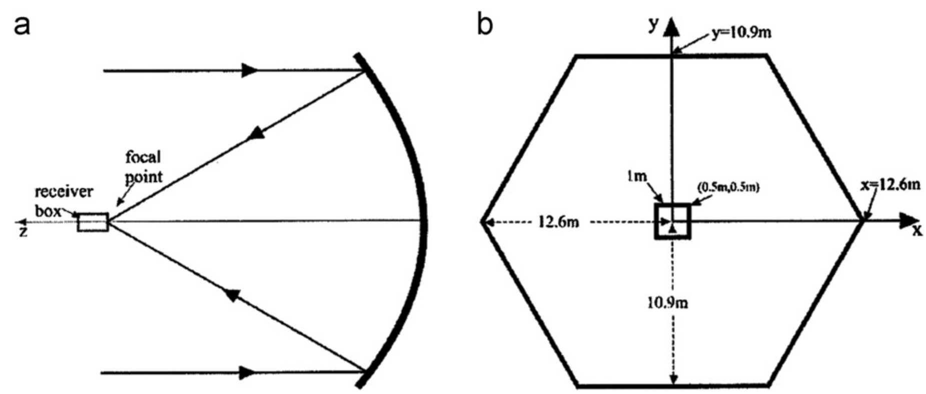

Fig. 22. Schematic view of the paraboloidal concentrator and its associated receiver box: (a) cross-section including the optical axis, (b) projection of the receiver box on the hexagonal periphery of the paraboloid.

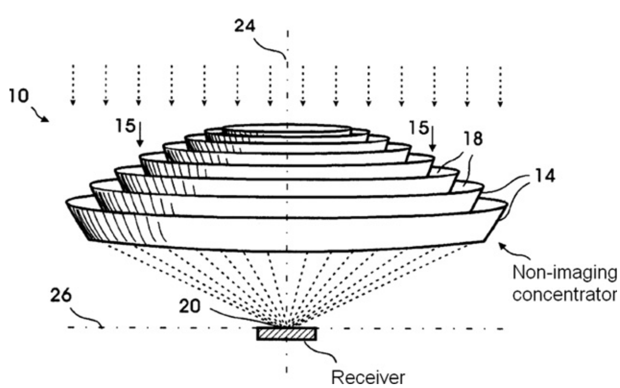

Fig. 23. Schematic view of the non-imaging system (10) includes a non-imaging concentrator comprising a plurality of coaxial ring-like elements (14) having inner reflective surface (18) and a receiver. Surfaces (18) receive incident sunlight (15) on the entrance aperture of concentrator and form a concentrated energy spot (20) on the target plane (26).

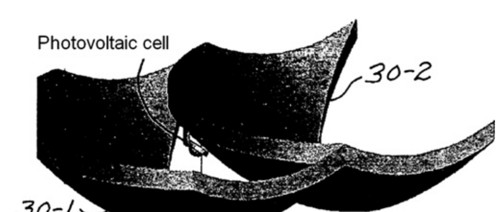

Fig. 24. Perspective view of two adjacent parabolic reflectors (30–1 & 30–2) with a photovoltaic cell.

Benitez et al. developed a two-mirror high concentration non-imaging optics that shares the advantage of present two-mirror imaging concentrators but also overcomes their main limitation like their trade-off between acceptance angle and irradiance uniformity [41]. From Fig. 25, the design is capable to work with an acceptance of 15 mrad half-angle and an average concentration over 800 suns (local concentration below 2000 suns).

As illustrated in Fig. 26, Lichy patented asymmetric, three dimensional, non-imaging, light concentrator adapted for use with a CPV cell [42]. The proposed solar concentrator has a hollow first stage formed by two pairs of facing reflective sides curved to different parabolas to form compound parabolic concentrator (CPC). The first stage CPC is optically coupled to a second stage solid CPC with two pairs of facing reflective sides curved to different parabolas. The second stage solid CPC with reflective index from 1.48 to 1.52 is optically coupled to a solid

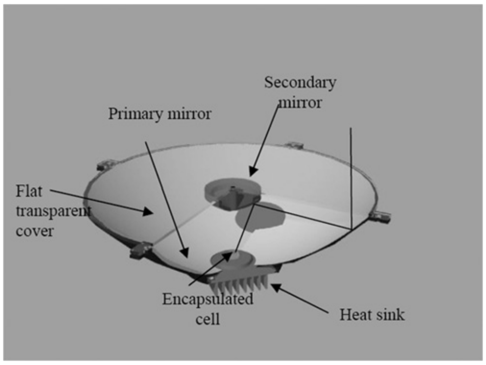

Fig. 25. CAD modal of the prototype design (a quarter of the primary, secondary and cover have been removed).

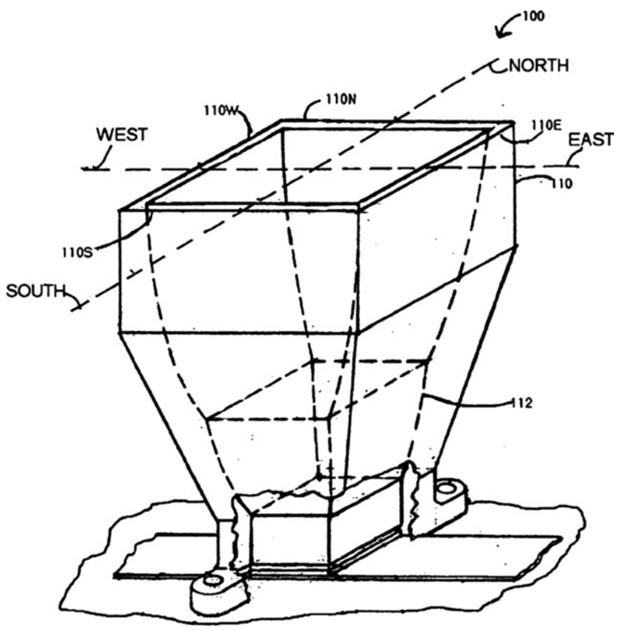

Fig. 26. Schematic illustration of an asymmetric, three-dimensional, non-imaging, compound parabolic concentrator (1 0 0): The hollow reflector (1 1 0) partially encloses and contains a solid reflector (1 1 2).

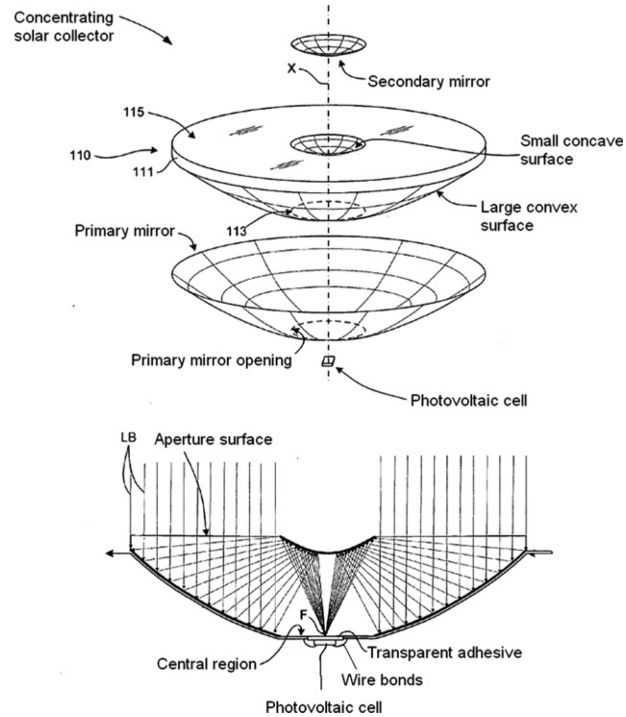

Fig. 27. An exploded perspective view showing an internal mirror, Cassegrain-type concentrating solar collector consisted of an optical elements (1 1 0), a photovoltaic cell located at central region (1 1 3), a primary mirror with an opening and a secondary mirror. Optical element is a solid, dish-like, light-transparent structure including an upper layer (1 1 1), a relatively large convex surface protruding from a lower side of upper layer, a substantially flat aperture surface (1 1 5) disposed on an upper side of upper layer and a relatively small concave surface defined in aperture surfaces.

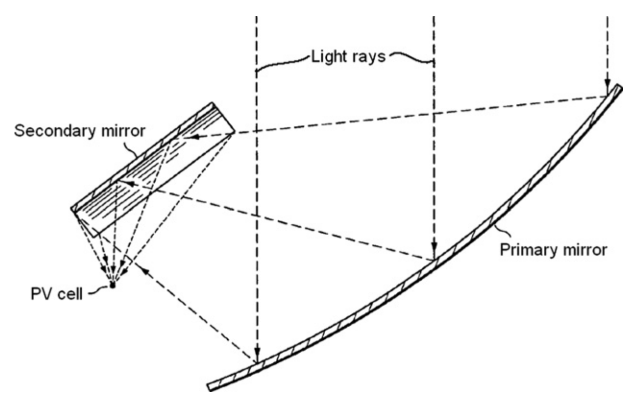

Fig. 28. A ray diagram illustrate an optical path for concentrated sunlight: Parallel rays are shown striking a primary mirror and reflecting towards reflective surface which serves as a secondary mirror and then to a focal point where PV cell is placed.

light diffuser. The solid light diffuser is optically coupled to the photovoltaic cell with a clear encapsulant. The whole concentrator is mounted on a metal substrate for thermal management. The proposed concentrator can operate efficiently with only single axis tracking of the sun in part because the reflective sides form orthogonal acceptance angles corresponding to the annual and daily apparent passage of the sun on Earth.

Fork and Maeda patented a Cassegrain-type concentrating solar collector cell including primary and secondary mirrors disposed on opposing convex and concave surfaces of a light-transparent optical element [43]. As shown in Fig. 27, light enters an aperture surrounding the secondary mirror toward the primary mirror, and is reflected by the primary mirror toward the secondary mirror, which re-reflects the light onto a photovoltaic cell mounted on a central region surrounded by the convex surface.

Neubauer and Gibson patented a solar concentrator consisted of a first reflective surface formed parabolic along a first axis and a second reflective surface formed parabolic along a second axis which is perpendicular to the first axis [44]. The focal length of the second reflective surface is shorter than the focal length of the first reflective surface for crossing the focal lines of the first and second reflective surfaces at a point as shown in Fig. 28. In other words, the whole concentrator consists of two parabolic troughs that are aligned along an optical axis. Hence, each parabolic trough can take parallel sunrays and focus them to a line. The parabolic axis of the first parabolic trough is oriented perpendicular to the parabolic axis of the second parabolic trough to focus the light from a line to a point.

Maeda patented beam integration for concentrating solar collector to concentrate sunlight onto a PV cell. Fig. 29 shows the whole system wherein an array of first optical elements that divide the sunlight into separate beams and a secondary optical system that integrates the separate beams in a defocused state at the image plane in order to form a uniform light distribution

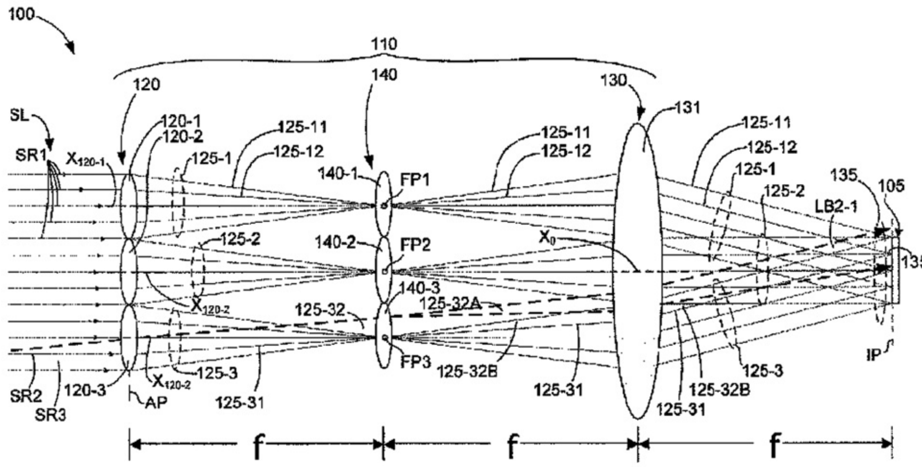

Fig. 29. A layout view showing a concentrating solar collector (1 0 0) that includes a CPV cell (1 0 5) supported in an image plane IP and a solar collector optical system (1 1 0). Solar collector optical system (1 1 0) includes a first array (1 2 0) with several first optical elements (120–1 to 120–3) that arranged in an aperture plane AP, a secondary optical system (1 3 0) with at least one secondary optical element (1 3 1), and an optical elements (140–1 to 140–3) disposed between first optical elements and secondary optical element.

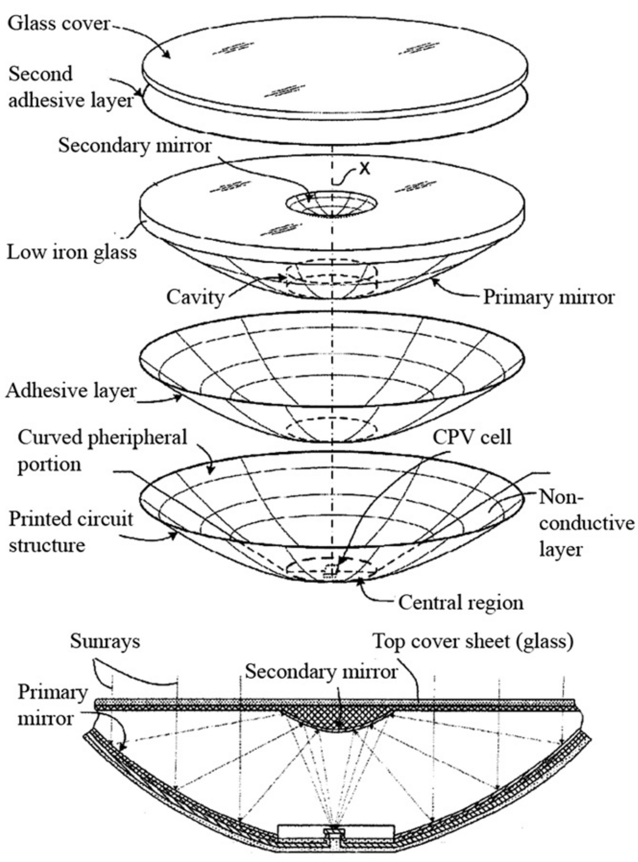

Fig. 30. An exploded perspective view (upper diagram) and a cross-sectional side-view (lower diagram) showing a laminated solar concentrating photovoltaic device.

pattern on the CPV cell [45]. The secondary optical system is positioned at a distance from the aperture plane, whereby the rays of each separate beam leaving the secondary optical element are parallel. The image plane (CPV cell) is located at the back focal point of the second imaging system, whereby all of the separate beams are superimposed on the PV cell in a defocused state.

Fork and Horne patented a laminated solar concentrating photovoltaic device as exploded in Fig. 30 in which concentrator elements (optics, CPV cells, and wiring) are laminated to form a composite, substantially planar structure [46]. Primary mirror and secondary mirror are disposed on convex and concave surfaces, respectively. Both primary and secondary mirrors are arranged such that, as shown in Fig. 30, sunrays traveling perpendicular to aperture surface. Sunrays entering optical element through a specific region of aperture surface is reflected by a corresponding region of primary mirror to an associated region of secondary mirror and from the secondary mirror to CPV cell. Top coversheet serves to protect secondary mirror from the harsh outdoor environment by providing a thin, optically transparent layer (glass) over aperture surface and secondary mirror.

Shifman patented a solar energy utilization system to be comprised of a Cassegrain-type concentrator and two solar radiation receiver components [47]. As depicted in Fig. 31, the first receiver component is designed to convert first part of the solar spectral energy into electrical energy, and the second receiver component is designed to convert second part of the solar spectral energy into electrical energy. The solar radiation concentrating optics comprises of a concave primary reflector and a convex secondary reflector. The secondary reflector is adapted to reflect solar radiation in the first part of the solar spectrum into the first receiver component and to transmit radiation in the second part of the solar spectrum into the second receiver component.

Draganov patented a solar concentrator with folded beam optical configuration allowing for compact, lightweight construction [48]. Reflective optics is employed, including dichroic mirror and antireflection coating, to remove unwanted infrared radiation from reaching the solar cell. In Fig. 32, the solar concentrator comprises of three reflecting surfaces. The primary mirror (concave surface) reflects solar radiation upward to the second reflecting surface (plane reflector) that is optically coupled to the primary mirror for reflecting the solar radiation downward to the tertiary mirror (concave surface). The tertiary mirror is configured to reflect the solar radiation upward again to the second reflecting surface in such a way that the solar radiation is then reflected from the second reflecting surface towards focal plane where photovoltaic cell is located.

Chong et al. proposed a non-imaging planar concentrator consisted of numerous square flat mirrors, capable of producing uniform sunlight and reasonably high concentration ratio [49,50]. The uniform concentrated light is formed from the superposition

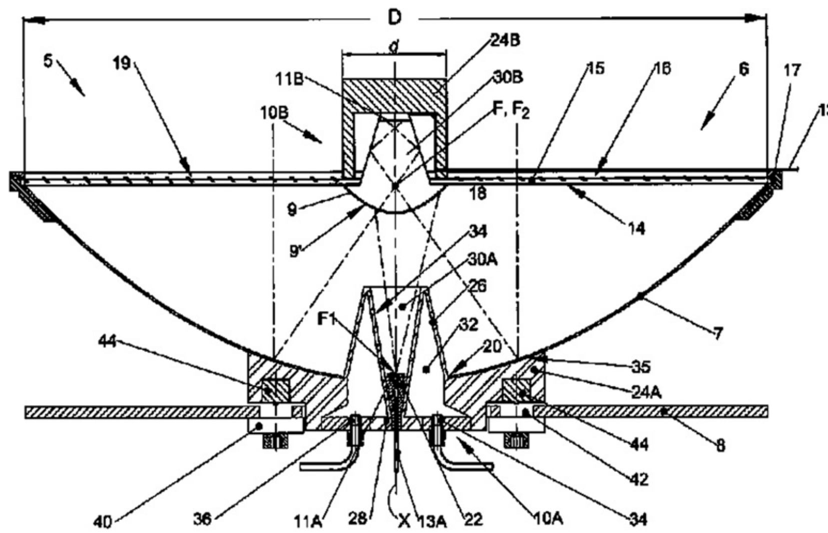

Fig. 31. Solar energy utilization unit (5) comprises of a solar radiation concentrating optics (6) including a concave primary reflector (7) and a concave secondary reflector (9) and a solar receiver designed to convert the radiation concentrated by the optics (6) into electrical energy. The solar receiver components (10A and 10B), each associated with either primary reflector (7) or secondary reflector (9) where (11A and 11B) may be a singular plate cell or an array of cells with different sensitivity wavebands.

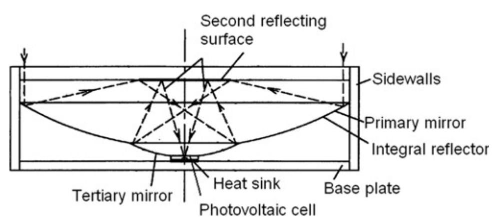

Fig. 32. The primary mirror and tertiary mirror form the integral reflector also called unitary reflector. The second reflecting surface 6 is a planar surface and is disposed between the primary mirror and the focal plane of the primary mirror. The PV cell is mounted on a heat sink with the base plate. On top of the solar concentrator, a piece of flat glass is spaced apart from the double curved reflector with sidewalls.

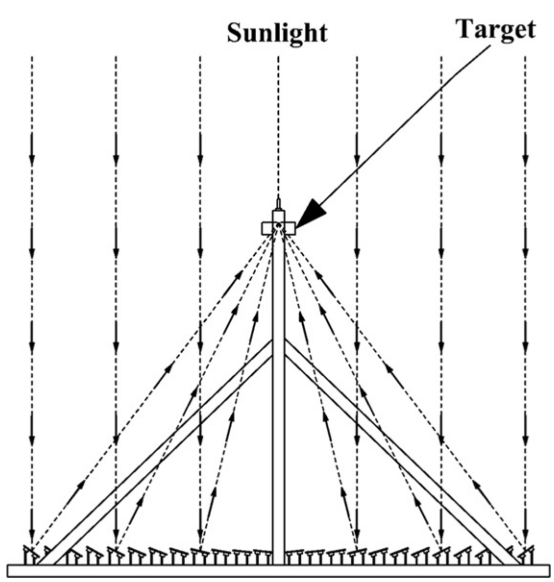

Fig. 33. Conceptual layout design of the non-imaging planar concentrator: Cross-sectional view of the planar concentrator to show how the individual mirror directs the solar rays to the target.

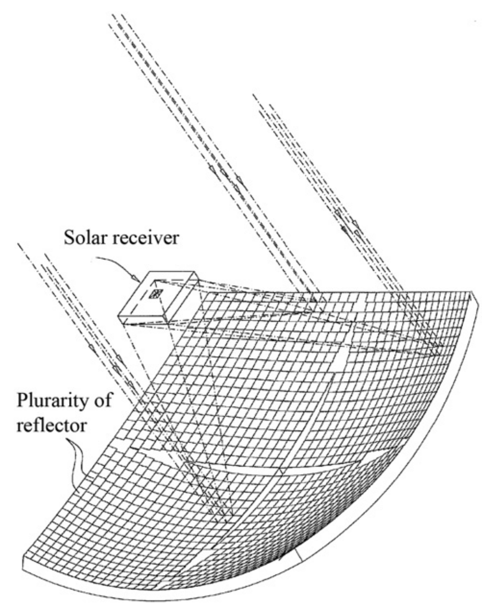

Fig. 34. Solar concentrator by Tsadka et al.: a simplified pictorial illustration of beam paths from some of the mirrors of the reflector portion to the receiver portion of the solar energy converter assembly.

of the flat mirror images into one as illustrated in Fig. 33. The prototype consisted of 360 flat mirrors, each with a dimension of 4.0 cm $\times$ 4.0 cm, to achieve the solar concentration ratio of 298 suns at focal distance of 78 cm.

Tsadka et al. patented the optical design of new concentrator with plurality of reflectors to reflect sunrays directly onto the solar receiver or CPV panel for electricity and heat generation as shown in Fig. 34 [51]. Plurality of reflectors arranged on support surface and each reflector is configured as well as aligned to reflect solar radiation with high degree of uniformity onto the solar receiver.

Chong et al. has filed the patent for non-imaging dish concentrator that provides uniform solar flux, match the square or rectangular solar images to the square or rectangular dimension of the photovoltaic receiver and produce high solar concentration ratio [52]. The non-imaging dish concentrator consists of plurality of optical assembly sets (see Fig. 35(a)) and each optical assembly

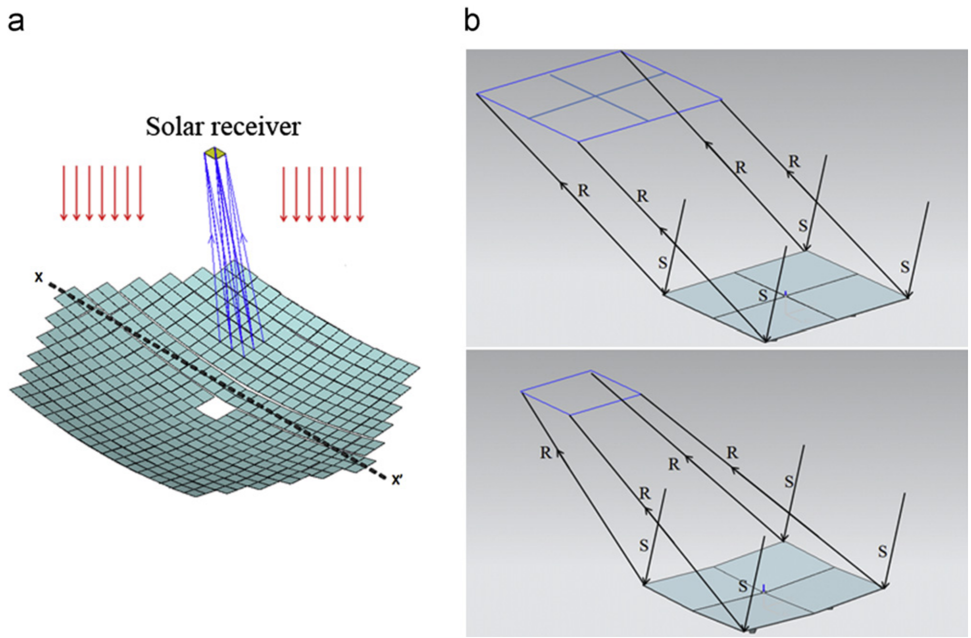

Fig. 35. (a) Non-imaging dish concentrator by Chong et al. consists of optical assembly set in which the solar concentration ratio is dependent on the applications by simply increasing or decreasing the total number of optical assembly sets, (b) The superposition of all the images of four flat component mirrors of each optical assembly set into one by inclining them relative to the pivot at the centre. Four flat mirrors are placed together to form one optical assembly set and they share one common pivot point at the meeting point. The shape of each mirror is either rectangular or square dependent on the solar cells arrangement at the photovoltaic receiver. The mechanism of inclining the four flat mirrors arrangement with a reference to the common pivot point at the centre results in the solar images of four component mirrors to superpose or overlap into one.

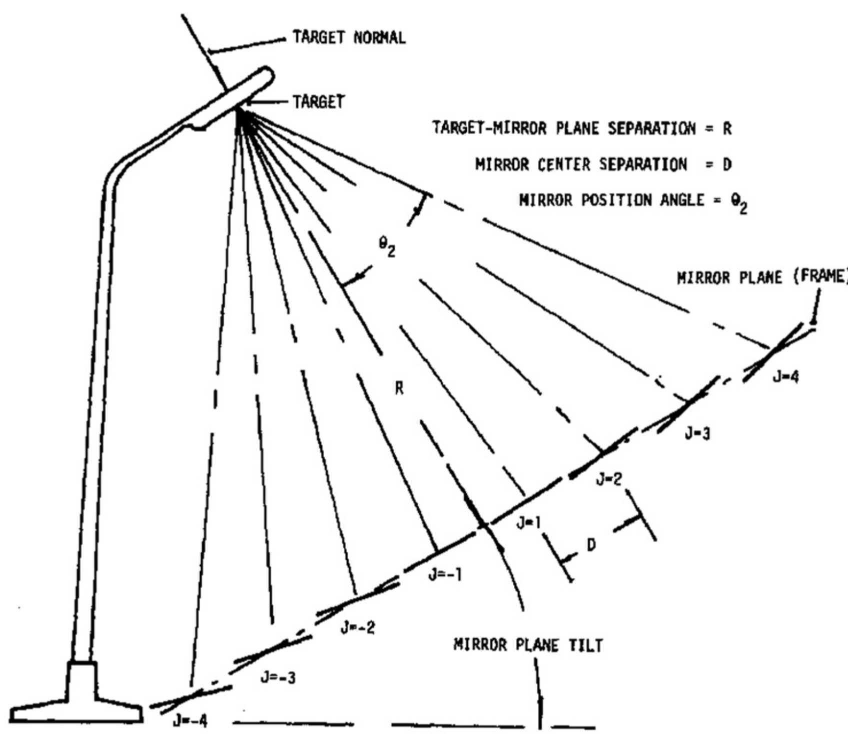

Fig. 36. Cross section, target-mirror geometries. Centers of mirrors lie in mirror frame plane. Mirrors may be moved individually (or in groups) to direct sun's image. In addition, target-mirror plane structure could be rotated and tilted to track sun.

set comprises of four flat mirrors placed together sharing one common pivot point at the centre (see Fig. 35(b)). Referring to Fig. 35(b), flat facet mirrors are used to ensure rectangular and uniform solar flux in which the superposition of all the images of four facet mirrors of each optical assembly set into one by inclining them relative to the pivot at the centre.

2.5. Central receiver system

Ittner proposed an array of directable mirrors as a photovoltaic concentrator [53]. The mirror field consists of a two dimensional matrix of mirrors which may be plane or focused. For simplicity, it is assumed that the centers of the mirrors all lie in a plane which

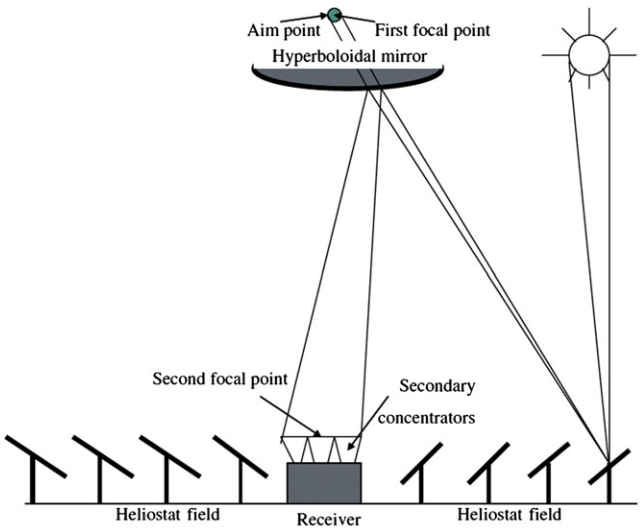

Fig. 37. The principle of tower reflector optics.

is centered on the photovoltaic target normal and is parallel to the plane of the target. The photovoltaic target normal thus defines the target mirror frame axis that may either be fixed in direction or arranged to track the sun in one or two dimensions (for instance, by rotating the arrangement as shown in the east-west direction about a vertical axis and by tilting the target-heliostat axis relative to the plane of the horizon). Independently, the individual mirrors may be moved so that they direct the sun's rays onto the plane of the target. Mirrors are positioned in two dimensions within the plane as shown in cross section in Fig. 36.

As illustrated in Fig. 37, Segal et al. presented the option to use the beam down optics of a solar tower system for large-scale and grid-connected CPV cells [54]. Two optical approaches for a large scale hybrid CPV and thermal power conversion at different spectral bands are proposed. In the first approach, the hyperboloid-shaped tower reflector is used as the spectrum splitter. Its mirrors can be made of transparent fused silica glass, coated with a dielectric layer, functioning as a band-pass filter. The transmitted band reaches the upper focal zone, where an array of PV modules is placed. The location of these modules and their interconnections depend on the desirable concentration level and the uniformity of the flux distribution. The reflected band is directed to the second focal zone near the ground, where a compound parabolic concentrator is required to recover and enhance the concentration to a level depending on the operating temperature at this target. In the second approach, the total solar spectrum is reflected down by the tower reflector. Before reaching the lower focal plane, the spectrum is split and filtered. One band can be reflected and directed horizontally to a PV array and the rest of the spectrum is transmitted to the lower focal plane. The system intended to operate under concentrated solar radiation in the range of 200–800 suns. The study shows that 6.5 MW from the PV array and 11.1 MW from a combined cycle can be generated starting from solar heat input of 55.6 MW.

3. Conclusion

The technology of CPV can be viewed as a potential major energy source in the future. The future cost of energy from conventional sources is a main factor determining how much society may be willing to pay for the social and environmental benefits of solar energy. A great revolution in solar electricity generation is underway due to the progress in the CPV materials and creative optical designs. Commercial multi-junction CPV technologies have already demonstrated solar cell efficiencies of about 40% under high concentrated solar irradiation of hundreds to thousands of suns [55]. On the other hand, dense array CPV receiver for 500 suns reflective dish has been successfully deployed with the efficiency ranging from 30% to 36% at six different locations in Australia, counting for more than 1 MWp of installed peak power [56].

Under these high concentrated solar irradiations, the cost of CPV is greatly dependent on the optical system. In this article, we have reviewed various optical systems proposed and patented by the world renowned authors and inventors. Despite many optical designs have been presented, the ultimate goal is to provide cost-effective, rigid, easy-manufactured and high efficient solutions to the CPV system either in small or large scale.

Acknowledgements

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